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SPACE ORDNANCE SYSTEMS, INC.

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A Study of the Sensitivity of Pyrotechnic Materials to Laser Energy

28 February 1969

Space Ordnance Systems, Inc.

Contract No. NAS7-670

for

National Aeronautics and Space Administration

Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena, California

This report documents in detail the work performed in studying the sensitivity of pyrotechnic materials to laser energy. The work was supported by contract No. NAS7-670.

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Abstract - A study has been undertaken to determine the sensitivity of some pyrotechnic materials to laser energy. The need for such studies is presented along with the approach taken to obtain data on the sensitivity of explosoves to laser energy. The data which is summarized and and discussed results in the establishment of a relative index of sensitivity for pyrotechnic materials to laser energy. Conclusions and recommendations are made based on the data observed and past experience with testing laser initiated explosive components.

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INTRODUCTION

The purpose of this study was to investigate the relative sensitivity of several pyrotechnic materials to laser energy. Various laboratories have been studying the effects of laser energy and normal light energy on explosive materials. Some of the information has been published and was helpful in this study. However, this investigation was oriented toward a specific application; that of using laser energy to initiate explosive components. The pyrotechnic materials selected to study were those typically utilized in explosive and propellant devices presently used on aerospace vehicles. The concept of laser ignition of explosive components on board a space vehicle would necessitate a 3-part system which would include a device to generate the laser energy, a means to convey the laser energy, and an explosive component capable of accepting the laser energy.

The potential advantages of such a system over the presently used electrical methods are increased safety and reliability. There presently exists a serious safety problem associated with electrically initiated devices (EED) due to electromagnetic radiation. On all space vehicles there are extremely long electrical cables and powerful radio and radar transmitting devices. There is on record numerous reports of inadvertant initiation of EED's due to "cross talk" in the electrical cables or by pick-up of electromagnetic radiation.[/(1)] These problems have led to the introduction of 1-watt/1-ampere no-fire initiators and exploding bridgewire (EBW) devices. These devices have reduced susceptibility to inadvertant initiation. However, the complexity of these devices has resulted in costs much higher than conventional EED's utilized to achieve the same degree of reliability.

Increased safety can be achieved with a laser initiated explosive device because the laser pulse or beam is a unique form of energy. In general it has not been observed naturally or expected to be generated except under very deliverate and positive means. Therefore, these devices would be immune to the present environments associated with space vehicles. Increased reliability would be realized because of the simplicity of the laser initiated explosive device. All of the safeguards necessary to achieve electrical immunity in the construction of EED's can be eliminated. The laser device would consist of a metal body to contain the explosive material and a window through which the laser energy could enter. Piping of the laser energy from the laser source to individual explosive components is possible with the use of fiber optics. Space Ordnance Systems, Inc. (SOS) was a pioneer in recognizing that laser energy can be a discriminating source for the initiation of explosive devices. SOS sponsored a program to study the feasibility of a laser initiated explosive system. The result of this study was the development of a compact laser (approximately eight pounds), a fiber optic laser transfer system, and a laser initiated explosive component. The system has been demonstrated and found to be feasible. Further studies showed that the system is reliable and that explosives as insensitive as RDX could be initiated in this system.

During the above investigation a very limited amount of time was spent on the investigation of laser sensitive explosive materials. To expand and better understand the capabilities of a laser system a more thorough study of laser sensitive pyrotechnic materials was needed. It was the intent of this study to investigate the sensitivity of selected pyrotechnic materials to laser initiation. The knowledge gained and the data generated could be applied to the design and development of laser systems similar to that developed by SOS. All of the work carried out in this study was without the use of fiber optics.

The laser phenomenon is a recent invention with approximately ten years of history. However, the theory which lead to the invention has been known for a longer period of time. Normally, materials absorb light and the light energy is converted to heat. These same materials when heated emit light with a spectral distribution which follows the black body radiation law. Some materials, depending on their chemical structure, show selective absorbtion of light in particular spectral ranges resulting in fluorescense or stimulated emission. Resonance phenomenon occurs when the light energy absorbed equals the energy difference between two energy levels in an atom or molecule. These phenomena are explained by quantum theory in which the energy of electrons, atoms, and molecules are at different energy levels or states. Electrons or atoms absorb light energy and are raised to excited states. When the excited material returns to its original or ground state the absorbed energy is released as electromagnetic radiation obeying the laws of quantum theory. The emission is non-coherent but has a special property in that the emission can be controlled.

Semi-transparent materials absorb light energy following an exponential law as a function of thickness. Reflectors can be placed at two faces of the material to act as reflecting surfaces and when the material is stimulated with light energy the stimulated emission, at a particular wavelength, can be amplified between the two reflectors. The amplification is analogous to an electronic feedback oscillator. If the light amplification is above a certain threshold then a stabilized release of the energy through a beam splitting type reflector can take place. The amplification has to be obtained by fixing the oscillating beam along a finite path which results in multiple oscillations. This can be done by accurately aligning the reflectors resulting in a well defined, direction controlled, stimulated radiation beam. This is known as lasing. Owing to various factors such as population inversion, transition life time, etc., not all materials can lase. Research in the past decade had uncovered a number of gases, doped crystals, and semiconductors capable of lasing.

In practice the laser has been used to project a high intensity, coherent beam of radiation. Some of the applications have been to use the intense energy to illuminate, melt, weld, perforate, or ignite materials. There are many other facets to which the laser has and can be adapted to. For this paper, we are concerned primarily with the ability of the intense laser energy in pulse form to cause ignition of pyrotechnic materials.[(3)]

Initiation of explosives by light was under study before the invention of the laser.[(2)] The light sources used were xenon flash lamps which inherently contained a number of disadvantages. The light output from a flash lamp has a large divergence and the light energy decreases very rapidly as a function of distance. There are limits to which the flash lamp can be driven requiring the sample under test to be placed quite close to the lamp.

By comparison the advantages of laser generated energy are primarily that the flux density equated in watts/unit area is much greater. The laser output has a relatively small beam divergence, approximately 5 milliradians. Attenuation of the beam in air is very small and an accurate energy determination is easily made with a calorimeter type energy converter. The laser beam is well defined and can be easily focused. It is quite simple to integrate the energy because the laser spectral band is very narrow, approximately 100Å spread.

However, the laser output can have a non-homogeneous energy distribution along the cross section of the beam. Due to the mechanism of "pumping" to obtain the laser the occurrence of "hot spots" within the beam is possible. Usually the hot spot occurs near the center of the beam in an irregular shape.

DESIGN OF THE EXPERIMENT

The investigation was primarily directed to the sensitivity of several pyrotechnic materials when initiated by a neodynium laser. The wavelength emanated by a neodynium laser is 10,600Å. One exception to this test method was that SOS-108 mix was also studied with a ruby laser (6943Å). Materials studied are listed in Table 1. The list of materials includes conductive mixtures, primary high explosives, secondary high explosives, delay mixtures, and propellants. The effects of a number of variables on the sensitivity were also considered and are listed as follows:

a. Particle size of the material

b. Compaction pressure of the sample

c. Laser pulse length

d. Laser beam area exposed to the sample.

The pyrotechnic materials were loaded into a steel ring as shown in Figure 1. An inside diameter of 0.4 inch for the sample holder was selected because the diameter of the neodynium laser rod is 0.4 inch. Five samples, for each condition cited above, were loaded for each explosive material. The sensitivity was to be determined by a fire, no-fire approach, i.e., to find two extreme levels of laser energy, one which would not initiate the sample and a second level which would. The remaining three samples would be used to find a mean energy to cause initiation. Prior to each test the laser was fired into a calorimeter to determine the exact number of joules emitted. It is assumed that for the same conditions the energy omitted is repeatable. In those cases in which the sample could not be initiated at the upper energy limit of the equipment an attempt would be made to initiate the material by lensing the energy.

The effect on sensitivity as a function of area of the beam would be determined by using a mask over the sample. The mask would be designed to reduce the area of the sample exposed to 1/4 of the area of the laser rod. Because the laser light is coherent and assuming the laser beam to be homogeneous then the energy density (J/in^2) will be the same for each condition.

Effects of pulse width on the sensitivity of the material was to be observed. The width of the laser pulse was to be controlled by varying the inductance in the laser power supply. Two pulse widths, one approximately 500 microseconds and the other approximately 1.5 milliseconds were to be used. During the actual test program it was found that the pulse width could not be controlled internally. Therefore a new approach was taken which will be discussed later.

In addition to the above, the reflectivity of the pressed explosive materials was to be determined over the wavelength range 4000 to 7000Å. A Bausch and Lomb Spectronic 505 capable of measurements between 4000 and 7000Å was used. This spectrum contains the 6943Å wavelength as emitted by the ruby laser. Testing at the 10,600Å wavelength (neodynium laser) required a special fixture wherein a c.w. yttrium aluminum garnet laser and dual photometer as shown in Figure 2 was needed. The laser beam is split immediately upon its emergence from the c.w. yttrium aluminum garnet laser which emits power precisely at the frequency of 10,600Å. The split beam is then directed onto two samples, one being a standard calibration block of magnesium oxide and the other the material under test. The light reflected from these two samples is detected by a matched pair of photodiodes having extreme accuracy. Electrically noting the difference in outputs will give the absolute absorption of the sample at 10,600Å. One of the inherent advantages in this system is that inconsistencies in the output of the yttrium aluminum garnet laser which is very difficult to control, of around 10 to 20 percent will not affect the output, as the energy incident upon the two samples will change together. Therefore, the system is self-tracking and does not have any error due to changes in input to the photodiodes. Calibration of the system is accomplished by using a single magnesium oxide block which is dissected. The matching faces are then placed at both input points and the unit adjusted to zero percent absorbance. The same technique is used with a block of graphite to adjust the 100 percent level.

The special reflectance fixture (for the 10,600Å) created some undesirable effects. The amount of light available on the diodes yielded only a few hundred millivolt output in these diodes. After differentiating the outputs the resulting output was only in the order of hundreds of microvolts. The fixture has the same basic features as the original set-up, in that a continuous read-out is available from the light source, to verify that the source keeps a constant output during the test. The outputs of both photodiodes are no longer differentiated, which yields a much higher output from the diode, thus increasing the signal to noise ratio.

An additional feature was built in the modified fixture. The photodiode measuring the reflectance is mounted such that is can be rotated over 180° in order to measure reflectance under different angles. The armature of this rotating diode is mounted on a potentiometer, which converts angle into voltage in a linear fashion. By feeding the photodiode output and the potentiometer output to an xy recorder, a plot can be obtained showing reflectance versus angle. The output of the diode, when rotated, will follow the expression:

$$I = I_{max} \cos Q$$

In this particular program, the angle Q is kept at 45^{o}. A magnesium oxide block is inserted in the sample holder. The resulting diode output corresponds with 100% reflection. Then a black light trap is inserted in the sample holder. This yields an output corresponding with 0% reflection. The test sample will give an output somewhere between 100% and 0% output reference.

Other areas of interest not directly related to the sensitivity study but of interest from the standpoint of laser application to explosive components were also considered. Because SOS had generated a great deal of pressure bomb data on its Apollo Standard Initiator (ASI) it was of interest to know if the pressure/time characteristics would vary as a function of the mechanism of initiation, i.e., electrically initiated or laser initiated. Another area os interest was the sensitivity to laser energy of some of the materials in Table 1 when they are confined in a housing designed for laser initiation.

TEST RESULTS

In order to better appreciate and understand the sensitivity results it will be advantageous to first review the reflectance data. All materials were tested for reflectivity at 10,600Å with the exception of SOS-108 mix which was also tested at 6943Å. Table 2 lists the percent reflectance under the various loading conditions at 6943Å. SOS-108 mix is dark grey in color and is expected to be a relatively good light absorber. Table 3 lists the same type of data obtained on all the materials studied at a wavelength of 10,600Å. The data shows that there is a considerable difference in the percent of light reflectance among the samples tested. Some of the samples showed little differences in reflectivity as a function of pressure and particle size while others showed a larger spread. It is recognized that particle size, loading pressure, binder, if any, and surface finish will all play a part in determining the reflectivity of the sample. In any laser application these parameters would have to be taken into consideration. It is expected that to maximize the sensitivity of a material for a laser initiated device it would be necessary to minimize reflective loses. During the reflectivity tests some of the high explosives such as lead azide, RDX, HMX, HNS, and PETN were found to be translucent to laser energy. This was determined by utilizing a helium neon cw gas laser of low energy and measuring the amount of laser energy passing through various thickness samples. Because the sample holders were designed to result in a thin wafer of explosive material it was felt that an error would be introduced if these materials were tested in this manner. To overcome this problem a sample holder as shown in Figure 3 was constructed to load the translucent materials. The same explosive weight used in the first sample holder would fill the cavity of the modified sleeve thus ruling out the loss of laser energy by transmission through the sample. The smaller inside diameter is compatible with the sensitivity testing since it would be necessary to lens the laser beam to a smaller diameter if initiation were to be expected.

The technique of determining laser sensitivity of the pyrotechnic materials under study is to vary the energy output of the laser beam until a mean energy to initiate the material was arrived at. The mechanism to vary the laser beam energy is to vary the voltage on the capacitor which functioned the flash lamp. It was observed that the laser pulse width varied as a direct function of the laser output. In order to maintain a constant pulse width it was decided to fix the potential on the capacitor so that a constant energy and pulse width would result. Attenuation of the energy would then be achieved by external filters. The Korad ruby laser pulse was characterized in this way. Some pertinent details about the ruby laser rod and Korad equipment are given below:

Manufacturer	Korad, Dept. of Electrical Products Division, Union Carbide
Diameter of ruby rod	0.370 inch
Manufactured by	Linde Products, Union Carbide
Area of ruby rod face	0.108 $inch^2$
Length of ruby rod	3.5 inches
Capacitor value	400 μf
Flash lamp	xenon, helical
Reflector cavity	White ceramic
Back mirror	100% reflectance @ 6943Å (gold)
Front mirror	50% reflectance @ 6943Å (gold)

A set of 23 calibrated glass filters was used to achieve the attenuation needed in this program. To achieve a given attenuation, varying numbers of glass discs (Corning Glass 0211)

1.0-inch in diameter and 6 mils thick were used. The discs are placed in an aluminum holder designed to fit the laser apparatus.

Table 4 lists the data obtained from the calibration tests. A theoretical calculation for transmission was also made based on the expression:

$$T = \left[1 - \left(\frac{n-1}{n+1}\right)^2\right]^2$$

<u>WHERE</u>

T = transmission

n = the index of refraction of the glass (typical value 1.50)

The experimental data was obtained by fixing the ruby laser to transmit 5.0 joules of energy. The filters were placed in line with the laser beam and the energy measured with a calorimeter or a photometer after passing through the filters. The theoretical and experimental data are in good agreement. As the transmission data were being generated the beam pattern was obtained on exposed polaroid film. The non-homogeneity of the beam was quite apparent as the size and shape of the beam area decreased and became more irregular as the attenuation was increased. To demonstrate that the pulse duration will be constant the following test was conducted. The laser output was fixed at 5 joules, attenuation was made when N*= 0, 5, 10, 15 and the pulse duration observed by oscilloscope traces for each attenuation. In each case, the pulse duration was 1.6 milliseconds. The same procedure was followed using the neodymium laser rod. Some details of the neodymium rod are given below:

Diameter	0.400 inch
Area	0.126 $inch^2$
Length	4.00 inches
Capacitance	400 μf
Lamp	Helical xenon
Back mirror	100% reflectance @ 1.06μ
Front mirror	65% reflectance @ 1.06μ
Manufacturer	Owens Illinois

The neodymium pulse width was 1.5 milliseconds. As a result of this calibration both the ruby and neodymium laser pulse lengths were well defined.

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*N = Number of glass discs

Numerous attempts were made, without success, to obtain a short duration pulse (approximately 500 microseconds) using the ruby rod. However it would be necessary that the RC time constant be significantly reduced and since the value of R is fixed by the flash lamp the only variable is the capacitor. Since the voltage must be increased if the capacitance is reduced, in order to maintain the energy it became necessary to increase the voltage level to above the self flash point of the xenon lamp. This limiting factor left a pulse still in excess of 500μsec. In lieu of this it was decided to obtain the shortest ruby pulse possible using the Korad equipment. It was found that a laser pulse duration of 1.1 milliseconds could be obtained when the input potential was fixed at 3450 volts resulting in a laser output energy of 0.43 joules. With these fixed conditions the laser beam was calibrated as a function of external attenuation. Table 6 summarizes the data for this calibration.

To obtain the short duration laser pulse using the neodynium rod a modification to the existing equipment was required. The modification consisted of replacing the helical xenon lamp in the Korad laser with a linear xenon lamp and omitting the water cooling feature.

The statistics of this system are given below:

Manufacture of the rod:	Owens Illinois Co. ED-3 rod, same as used in Macro-Pak
Diameter of the rod:	0.4 inch
Area of the rod:	0.126 inch^2
Effective length of the rod:	4.0 inches
Capacitance:	200 microfarads
Inductance:	100 microhenry
Lamp:	EG&G FX 45-4c linear xenon Flash lamp OD = 9mm ID = 7mm Arc length = 4.0 inches
Mirror:	Back mirror: 100% dielectric coated Front mirror: 75% dielectric coated The percentages are at 1.06 microns
Reflector:	Close wrapped aluminum foil (5 mil thick)
Cooling:	Air cooling with a fan sitting near the laser head.

At the 5 joule level the pulse duration is 450 microseconds.

The calibration data for this system is summarized in Table 7.

With the calibration of the laser pulses completed testing of the pyrotechnic materials commenced. A great deal of data was generated covering a number of parameters. Tables 8 through 19 report the data under the various conditions tested. Energy density (J/in^2) is calculated from the etched area observed on a piece of exposed polaroid film. It is necessary to have an energy density of at least 8.5 J/in^2 before a change in the polaroid paper is observed. The pattern observed can then be said to be made up of the high intensity spikes within the laser beam constituting an average "hot spot" energy. Items 13 through 23 of Table 1 were tested in the same manner as the other materials but failure to initiate in all cases resulted. The energy was then increased to 15 joules without successful initiation. At the 15-joule energy level the beam was focused through a lens resulting in an energy density of approximately 1500 J/in^2. PETN and RDX under confined conditions is known to initiate at density levels of about 500 J/in^2. The reason for non-ignition of these materials at the 1500 J/in^2 level is assumed to be a lack of proper confinement. If the materials were confined in a laser initiated type device, once a chemical reaction started, the pressure from the reaction products, which is necessary for propagation, is maintained. Under the conditions of no confinement, which was the case in these tests, the explosive surface exposed to the laser energy showed that some chemical reaction occurred and that considerable break-up of the explosive column occurred for a depth of about 50 mils. It is postulated that chemical reaction started but failed to propagate because the reaction products were not confined. Other indications of chemical reaction were color changes and reaction products deposited on the focusing lens located about one inch from the explosive sample.

The results of the materials which were initiated show that the more sensitive materials like SOS-108 mix, lead styphnate, and lead azide were not sensitive to particle size, loading pressure, and pulse width. However those materials which were less sensitive to laser energy, loading pressure and pulse width appear to effect their sensitivity to laser initiation. The materials have been ordered in Table 20 with the material most sensitive to laser initiation first, using the average energy density of all conditions tested. The listing has a different ordering when compared with sensitivity to impact, friction, electrostatics, and heat. However, if we take into consideration the reflectivity of the material, then an ordering more consistent with other methods of sensitivity testing results. Table 21 lists the new ordering. If one considers the material from the standpoint of laser sensitivity only, then the ordering in Table 20 is valid.

A comparison was made of the output (P/T characteristics) of a typical EED with that of the same device initiated by laser energy. The Apollo Standard Initiator (ASI) was selected for the test. A second ASI was converted to accept laser energy in lieu of the electrical header. Details of the construction of each device are given below:

	ASI	SOS Laser Initiator
Energy Input	Electric Current, Alumina	Laser Energy
Mechanism	Pinheader 2 mil SS 304 Bridgewire (resistance 1 ohm) Pinheader ID = 0.200"	Window (Silicon) ID + 0.250"
Primary Mix	65 mg SOS 108 pressed @ 10K psi	65 mg SOS 108 pressed @ 10K psi
Secondary Mix	60 mg SOS 108 hand press	60 mg SOS 108 hand press
Body	SS 16 3/8-24 screw	SS 17 3/8-24 screw

The test was conducted by initiating the devices in a 10cc bomb and observing the P/T characteristics via a Kistler 601A transducer. The resultant oscilloscope traces are shown in Figure 4. The output of the two devices is very similar and independent of the mechanisms of initiation.

It was of interest to test some of the materials studied in an actual applications configuration. That is, to load the materials in a housing which would simulate a laser initiated explosive device. In addition it was decided to dope some of the materials in an attempt to make them more sensitive to laser energy. Figure 5 illustrates the construction of the laser initiated device. The materials tested and the manner in which they were doped and loaded is given in Table 22. The devices were placed in a safety chamber with a steel witness block next to the output end. By means of a hole in the safety chamber the laser beam was focused on the window of the device. The distance from the laser rod to the window was 5 inches. The energy output of the laser was set at 5 joules. Each device was given one pulse. Of the samples tested only sample No. 9 (AlC10-iron), No. 10(SOS-108), No. 12(Mg/teflon-no dope), No. 14(SOS-108, 10% microballoons), and No. 16(Mg/teflon, 10% microballoons) were initiated.

Examination of the windows of those which had not fired disclosed marring of the surface. Further attempts to initiate them would not yield valid data. Those devices which did initiate did not cause a dent in the steel blocks. This is reasonable since these materials do not normally detonate. It was expected that SOS-108 mix would ignite because of the past history of this material. Because of the sensitiveness of Mg/Teflon and AlClO No 2 - (iron) as determined in Table 20 it would have been expected that B/KNO_3 would have also initiated under these conditions. There is no explanation why B/KNO_3 did not initiate.

DISCUSSION

An initial step has been taken toward understanding the parameters involved in developing laser initiated explosive components. Assumptions were made at the start of this study, which during the course of the investigation were shown to be erroneous. As in all new fields of scientific endeavor more questions have been raised than were answered. However, Space Ordnance Systems, Inc. has demonstrated that a laser system is feasible.

This study represents a part of the work still required to be done before the maximum advantages of safety and reliability can be realized from a laser system for the initiation of explosive components. Major areas for investigation are; a) developing small, compact, high energy laser packages, b) optimizing designs of laser initiated explosive components, c) investigate fiber optics, and d) study all the interfaces in the system.

A laser ignition system will have to transfer its energy through fiber optics to the laser initiated device. An advantage here is that fiber optic materials are immune to electromagnetic radiation. However, one must contend with the high light attenuation in fiber optics (approximately 10% per foot). Q-switched laser output is another approach to laser initiated devices. Because the Q-switched pulse is very short in duration (nanoseconds) the high density energy damages the fiber optics preventing transmission. This represents another area for investigation.

The energy density, calculated for the samples tested, is based on the area effected when the laser beam is registered on developed polaroid fiber and not the diameter of the laser rod. The area is not circular but irregular and displaced from the center. The minimum light density (J/in^2) necessary to effect the film has been determined to be 8.5 J/in^2. This means that a large part of the laser energy is outside the beam pattern. If one externally attenuates the beam by inserting filters, as was done in this study, then the hottest region in the beam will be observed when additional attenuation will cause the pattern to disappear. This final pattern is considered the "hot spot" and is believed to be the energy causing ignition of the pyrotechnic materials. This theory is supported by the fact that there was little difference in sensitivity for a given material, between full beam and partial beam test results. The partial beam tests were conducted such that the hot spot was focused on the exposed area.

CONCLUSIONS

Based on the data collected and observations made in the foregoing study the following conclusions are drawn:

1. Particle size and loading pressure appear to influence the laser sensitivity of a pyrotechnic material.
2. The sensitivity of the pyrotechnic material is not a function of total energy but energy density.
3. The laser beam used in this study was not homogeneous.
4. The reflectivity of the sample under test influences its laser sensitivity.

5. In general the length of the laser pulse did not appear to effect the sensitivity of the sample except in several cases. In these instances the longer pulse length used in this program was more effective in causing ignition.

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2. "Fast Reactions in Solids"; F. P. Bowden and A. D. Yoffe

3. Report 6221, "LEED Systems (Laser Energized Explosive Device)"; Don J. Lewis, Space Ordnance Systems, Inc. 1 March 1968.

Table 1

Pyrotechnic Materials Studied

1. SOS-108 (Ruby)
2. SOS-108 (Neodymium)
3. Zr-$KClO_4$ 98% with Silicone Res. 2% GE Silicone Res. in GE-SRg8
4. Boron Pellets
5. Mag/Teflon Pellets
6. ALCLO No. 1 Lead
7. ALCLO No. 2 Iron
8. Delay Mix 176
9. Delay Mix 177
10. Lead Azide Dextrinated
11. P.V.A. Lead Azide Charge
12. Lead Styphnate
13. PETN
14. RDX (Virgin)
15. DIPAM
16. HMX
17. HNS
18. Sat Urethane Metalized As Cast
19. Sat Urethane Non-Metalized
20. Polyurethane Metalized*
21 AS18, Machined
22. AS19, Machined
23. AS20, Machined

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* (540) As Cast

Table 2

Selected Reflectance Results Obtained Under Various Loading and Particle Size Conditions for SOS Mix 108 at 6943Å (Continuously measured from 4000Å to 7000Å)

Particle Size	Loading Pressure	%Reflectance
Thru 100 mesh	10K psi	13.5
Thru 100 mesh	50K psi	13.0
Thru 400 mesh	10K psi	13.9
Thru 400 mesh	50K psi	17.2

Table 3

Reflectance at 10,600Å for Various Materials Under Various Loading Conditions

Material	Particle Size (mesh)	Loading Pressure (K psi)	Reflectance (%)
SOS 108 Mix	-100	10	10.5
	-100	50	13.2
	-400	10	8.8
	-400	50	11.1
$Zr-KClO_4$	-100	10	10.5
	-100	50	11.0
	-400	10	10.7
	-400	50	11.5
(B/KNO_3) Boron Pellets	---	10	6.2
	---	50	7.2

Table 3 (cont)

Material	Particle Size (mesh)	Loading Pressure (K psi)	Reflectance (%)
Mg/Teflon Pellets	--- ---	10 50	82.3 83.0
AlC10 No.1(lead)	--- ---	10 50	90.5 92.0
AlC10 No.2(Iron)	--- ---	10 50	24.0 44.0
Delay Mix 176	--- ---	5 10	34.0 31.8
Delay Mix 177	--- ---	5 10	46.1 44.5
Dextrinated Lead Azide	--- ---	2 10	86.3 79.3
P.V.A. Lead Azide	--- ---	2 10	85.5 86.5
Lead Styphnate	-100 -100	2 10	65.3 76.8
PETN	Class 1 Class 1 Class 4 Class 4	10 50 10 50	88.5 --- * 71.0 --- *
RDX	-325 60-100	10 50	80.3 73.6
Dipam	--- ---	10 50	94.0 --- *
HMX	-325 -325	10 50	80.0 --- *
HNS	-325 -325	10 50	87.8 --- *

Table 3 (cont)

Material	Particle Size	Loading Pressure	Reflectance
Sat.Cast			
Urethane:			
Metalized	---	---	11.0
Non-Metalized	---	---	33.0
Polyurethane:			
Metalized	---	---	12.0
AS18 Machined	---	---	†
AS19 Machined	---	---	†
AS20 Machined	---	---	†

* Compaction at 50K psi in the original sample holder was not possible.

† Reflectivity samples not supplied.

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Table 4

Calibration of Glass Filters and Laser Beam Area
As a Function of Laser Energy for the Ruby Rod
(Case 1)

NUMBER OF GLASS FILTERS (N)	% T (THEORETICAL)	% T (EXPERIMENTAL)	LASER ENERGY (JOULES)	AREA OF BEAM (INCH^2)
0	100	100	5.0	0.172
1	92.0	91.8	4.6	0.162
2	84.64	84.0	4.3	0.152
3	77.87	77.0	3.8	0.150
4	71.64	71.5	3.55	0.128
5	65.91	65.0	3.25	0.115
6	60.64	61.0	3.05	0.108
7	55.79	55.5	2.75	0.093
8	51.33	52.0	2.6	0.087
9	47.22	47.0	2.35	0.082
10	43.44	43.5	2.15	0.075
11	39.96	40.0	2.0	0.073
12	36.76	36.0	1.8	0.065
13	33.82	33.0	1.64	0 062
14	31.11	30.0	1.5	0.055
15	28.62	28.0	1.4	0.045
16	26.33	26.0	1.3	0.025
17	24.22	24.0	1.2	0.021
18	22.28	22.0	1.1	0.013
19	20.49	20.0	1.0	0.011
20	18.85	19.0	0.95	0.0087
21	17.34	17.5	0.87	0.005
22	15.95	16.0	0.8	0.0025
23	14.67	14.0	0.7	------

T = transmission
Pulse width 1.6 milliseconds

Table 5

Calibration of Glass Filters and Laser Beam Area
As a Function of Laser Energy for the Neodynium Rod
(Case 1)

NUMBER OF GLASS FILTERS (N)	% T (THEORETICAL)	% T (EXPERIMENTAL)	LASER ENERGY (JOULES)	AREA OF BEAM (INCH^2)
0	100	100	5.0	0.150
1	92	92.5	4.65	0.145
2	84.64	84.5	4.35	0.140
3	77.87	78.0	3.90	0.132
4	71.64	71.5	3.56	0.122
5	65.91	66.0	3.30	0.115
6	60.64	60.5	3.04	0.108
7	55.79	56.0	2.80	0.098
8	51.33	51.5	2.57	0.085
9	47.22	47.5	2.37	0.075
10	43.44	43.5	2.17	0.063
11	39.96	40.0	2.0	0.047
12	36.76	36.5	1.83	0.040
13	33.82	34.0	1.7	0.037
14	31.11	31.5	1.58	0.035
15	28.62	28.5	1.42	0.023
16	26.33	26.5	1.32	0.020
17	24.22	24.5	1.23	0.011
18	22.28	22.5	1.12	0.0075
19	20.49	20.5	1.02	0.005
20	18.85	19.0	0.95	0.0025
21	17.34	17.5	0.87	------

T = Transmission

Pulse width 1.5 milliseconds

Table 6

Calibration of Glass Filters and Laser Beam Area as a Function of Laser Energy for the Ruby Rod (Case 2)

NUMBER OF GLASS FILTERS (N)	% T (THEORETICAL)	% T (EXPERIMENTAL)	LASER ENERGY (JOULES)	AREA OF BEAM ($INCH^2 \times 10^{-4}$)
0	100	100	0.43	225
1	92.0	91.9	0.39	188
2	84.64	84.0	0.36	138
3	77.87	77.5	0.33	125
4	71.64	71.5	0.31	112
5	65.91	65.5	0.28	88
6	60.64	61.0	0.26	76
7	55.79	55.5	0.24	62
8	51.33	51.5	0.22	25
9	47.22	47.0	0.20	17
10	43.44	43.5	0.18	--

T = Transmission
Pulse width 1.1 milliseconds

Table 7

Calibration of Glass Filters and Laser Beam Area As a Function of Laser Energy for the Neodynium Rod (Case 2)

NO. OF GLASS FILTERS	% T (THEORETICAL)	% T (EXPERIMENTAL)	LASER ENERGY (JOULES)	AREA OF BEAM ($INCH^2$)
0	100	100	5.0	0.178
1	92.0	92.3	4.62	0.165
2	84.64	84.5	4.22	0.152
3	77.87	78.0	3.90	0.146
4	71.64	71.6	3.58	0.138
5	65.91	66.0	3.30	0.130
6	60.91	60.5	3.06	0.125
7	55.79	56.0	2.80	0.115
8	51.33	51.5	2.57	0.112
9	47.22	47.5	2.37	0.102
10	43.44	43.5	2.16	0.100
11	39.96	40.0	2.0	0.097
12	36.76	36.6	1.82	0.093
13	33.82	34.0	1.70	0.090
14	31.11	31.5	1.58	0.087
15	28.62	28.7	1.43	0.082
16	26.33	26.5	1.33	0.077
17	24.22	24.1	1.21	0.072
18	22.28	22.1	1.10	0.060
19	20.49	20.5	1.02	0.043
20	18.85	18.7	0.97	0.038
21	17.34	17.5	0.88	0.033
22	15.95	16.0	0.80	0.030
23	14.67	14.8	0.74	0.025
24	13.49	13.5	0.67	0.018
25	12.41	12.5	0.63	0.013
26	11.41	11.5	0.58	0.010
27	10.55	10.6	0.53	0.0075
28	9.66	9.5	0.47	-

T = Transmission

Pulse width 450 microseconds

Table 8

Mean Laser Energy Necessary to Initiate SOS-108 Mix Using the Ruby Rod

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 10K psi			
			FULL BEAM		PARTIAL BEAM	
			SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
ENERGY (joules)	-100	13.9	0.25	1.0	0.27	1.22
ENERGY (j/in^2) DENSITY			11.0	10.6	11.9	11.6
ENERGY (joules)	-400	13.5	0.31	1.22	0.3	1.28
ENERGY (j/in^2) DENSITY			13.0	11.6	13.0	12.7
			LOADING PRESSURE 50K psi			
ENERGY (joules)	-100	17.2	0.33	1.16	0.32	1.43
ENERGY (j/in^2) DENSITY			14.0	11.6	14.0	13.8
ENERGY (joules)	-400	13.0	0.4	1.59	0.4	1.62
ENERGY (j/in^2) DENSITY			16.6	15.5	16.6	15.5

Short pulse 1.1 milliseconds
Long pulse 1.6 milliseconds

Table 9

Mean Laser Energy Necessary to Initiate SOS-108 Mix

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 10K psi — FULL BEAM — SHORT PULSE	FULL BEAM — LONG PULSE	PARTIAL BEAM — SHORT PULSE	PARTIAL BEAM — LONG PULSE
ENERGY (joules)	-100	10.5	0.58	1.11	0.58	1.27
ENERGY (j/in^2) DENSITY			9.4	10.2	9.4	11.0
ENERGY (joules)	-400	8.8	0.74	1.46	0.74	1.43
ENERGY (j/in^2) DENSITY			11.9	12.8	11.9	12.8
			LOADING PRESSURE 50K psi			
ENERGY (joules)	-100	13.2	0.79	1.43	0.76	1.40
ENERGY (j/in^2) DENSITY			12.8	12.8	11.9	12.8
ENERGY (joules)	-400	11.1	0.93	1.80	0.95	2.07
ENERGY (j/in^2) DENSITY			15.0	16.3	15.0	17.9

NOTE: Neodymium Rod
Short pulse 450 microseconds
Long pulse 1.5 milliseconds

Table 10

Laser Sensitivity Test Results for Zr-$KClO_4$ Mix

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 10K psi — FULL BEAM — SHORT PULSE	FULL BEAM — LONG PULSE	PARTIAL BEAM — SHORT PULSE	PARTIAL BEAM — LONG PULSE
ENERGY (joules)	-100	10.5	0.48	0.98	0.49	0.95
ENERGY (j/in^2) DENSITY			7.6	8.5	7.6	8.5
ENERGY (joules)	-400	10.7	0.48	0.87	0.48	0.85
ENERGY (j/in^2) DENSITY			7.6	7.8	7.6	7.8
			LOADING PRESSURE 50K psi			
ENERGY (joules)	-100	11.0	0.54	0.96	0.48	0.95
ENERGY (j/in^2) DENSITY			8.5	8.5	7.6	8.5
ENERGY (joules)	-400	11.5	0.53	0.95	0.53	0.96
ENERGY (j/in^2) DENSITY			8.5	8.5	8.5	8.5

NOTE: Neodynium Rod
Short pulse 450 microseconds
Long pulse 1.5 milliseconds

Table 11

Laser Sensitivity Test Results for Boron Pellets (B/KNO_3)

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 10K psi			
			FULL BEAM		PARTIAL BEAM	
			SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
ENERGY (joules)		6.2	1.10	1.01	1.22	1.02
ENERGY (j/in^2)			17.8	9.3	19.4	9.3
			LOADING PRESSURE 50K psi			
ENERGY (joules)		7.2	2.15	1.72	2.39	1.71
ENERGY (j/in^2) DENSITY			35.0	15.3	38.2	15.2

Table 12

Laser Sensitivity Test Results for Mg/Teflon Pellets

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 10K psi			
			FULL BEAM		PARTIAL BEAM	
			SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
ENERGY (joules)		82.3	5.5	3.35	5.4	3.24
ENERGY (j/in^2) DENSITY			85.0	29.5	85.0	29.5
			LOADING PRESSURE 50K psi			
ENERGY (joules)		83.0	5.5*	13.0	5.5*	13.0
ENERGY (j/in^2) DENSITY			=100	74.5	=100	74.5

*Beam was lensed

NOTE: Neodynium Rod
Short pulse 450 microseconds
Long pulse 1.5 milliseconds

Table 13

Laser Sensitivity Test Results for AlC10 No. 1 (Lead)

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 10K psi			
			FULL BEAM		PARTIAL BEAM	
			SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
ENERGY (joules)		90.5	1.80	2.6	1.7	2.57
ENERGY (j/in^2) DENSITY	--		27.3	23.0	27.3	23.0
			LOADING PRESSURE 50K psi			
ENERGY (joules)		92.0	3.50	7.4	3.82	7.4
ENERGY (j/in^2) DENSITY			57.5	68.0	62.8	68.0

Table 14

Laser Sensitivity Test Results for AlC10 No. 2 (Iron)

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 10K psi			
			FULL BEAM		PARTIAL BEAM	
			SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
ENERGY (joules		24.0	2.57	3.2	2.55	3.25
ENERGY (j/in^2) DENSITY			41.4	29.5	41.4	29.5
			LOADING PRESSURE 50K psi			
ENERGY (joules)		44.0	4.2	7.15	4.65	7.10
ENERGY (j/in^2) DENSITY			67.0	63.0	74.4	63.0

NOTE: Neodynium Rod
Short pulse 450 microseconds
Long pulse 1.5 milliseconds

Table 15

Laser Sensitivity Test Results for Delay Mix 176

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 5K psi			
			FULL BEAM		PARTIAL BEAM	
			SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
ENERGY (joules)	—	34.0	0.87	1.59	0.87	1.59
ENERGY (j/in^2) DENSITY			14.0	14.0	14.0	14.0
			LOADING PRESSURE 10K psi			
ENERGY (joules)	—	31.8	0.95	1.56	0.86	1.54
ENERGY (j/in^2) DENSITY			15.0	14.0	14.0	14.0

Table 16

Laser Sensitivity Test Results for Delay Mix 177

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 5K psi			
			FULL BEAM		PARTIAL BEAM	
			SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
ENERGY (joules)	—	46.1	1.22	2.17	1.32	2.17
ENERGY (j/in^2) DENSITY			19.4	19.4	21.3	19.4
			LOADING PRESSURE 10K psi			
ENERGY (joules)	—	44.5	1.43	2.35	1.43	2.38
ENERGY (j/in^2) DENSITY			23.0	21.2	23.0	21.2

NOTE: Neodynium Rod
Short Pulse 450 microseconds
Long Pulse 1.5 milliseconds

Table 17

Laser Sensitivity Test Results for Dextrinated Lead Azide

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 2K psi			
			FULL BEAM		PARTIAL BEAM	
			SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
ENERGY (joules)	—	86.3	1.96	3.6	2.0	3.52
ENERGY (j/in^2) DENSITY			32.1	32.0	32.1	32.0
			LOADING PRESSURE 10K psi			
ENERGY (joules)	—	79.3	1.60	2.75	1.6	2.75
ENERGY (j/in^2) DENSITY			25.3	25.0	25.3	25.0

Table 18

Laser Sensitivity Test Results for Polyvinyl Alchohol Lead Azide

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 2K psi			
			FULL BEAM		PARTIAL BEAM	
			SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
ENERGY (joules)	—	85.5	1.43	2.65	1.5	2.80
ENERGY (j/in^2) DENSITY			23.0	23.0	23.0	25.0
			LOADING PRESSURE 10K psi			
ENERGY (joules)	—	86.5	1.30	2.15	1.22	2.12
ENERGY (j/in^2) DENSITY			21.3	19.4	19.4	19.4

NOTE: Neodynium Rod
Short pulse 450 microseconds
Long pulse 1.5 milliseconds

Table 19

Laser Sensitivity Test Results for Lead Styphnate

	PARTICLE SIZE (mesh)	% REFLECTANCE	LOADING PRESSURE 2 Kpsi			
			FULL BEAM		PARTIAL BEAM	
			SHORT PULSE	LONG PULSE	SHORT PULSE	LONG PULSE
ENERGY (joules)	-100	65.3	0.56	0.98	0.58	0.98
ENERGY (j/in^2) DENSITY			9.4	8.5	9.4	8.5
			LOADING PRESSURE 10 Kpsi			
ENERGY (joules)	-100	76.8	0.45	0.85	0.53	0.87
ENERGY (j/in^2) DENSITY			8.5	7.8	8.5	7.8

NOTE: Neodynium Rod
Short pulse 450 microseconds
Long pulse 1.5 milliseconds

Table 20

Sensitivity Ordering of Materials
to Laser Energy

Number	Material	Approximate Energy Density to Initiate (J/in^2)
1	Zr-$KClO_4$	8
2	Lead Styphnate	9
3	SOS=108 (Neodynium)	12
4	SOS-108 (Ruby)	13.5
5	Delay Mix 176	14.5
6	Delay Mix 177	21
7	PVA Lead Azide	22
8	Boron Pellets (B/KNO_3)	28
9	Dextrinated Lead Azide	29
10	AlCLO No. 1 (lead)	42
11	AlCLO No. 2 (iron)	54
12	Mg/teflon	85

Table 21

Sensitivity Ordering of Materials Based on Reflectivity

Number	Material	Adjusted Energy Density to Initiate (J/in^2)
1	Lead Styphnate	2.7
2	PVA lead azide	3.1
3	AlCLO No. 1 (lead)	4
4	Dextrinated lead azide	5
5	Zr-$KCLO_4$	7.1
6	Delay Mix 176	10
7	SOS-108 (Neodynium)	10.7
8	Delay Mix 177	11.6
9	SOS-108 (Ruby)	11.6
10	Mg/teflon	15
11	Boron Pellets (B/KNO_3)	26
12	AlCLO No. 2 (Iron)	36

Adjusted Energy = Energy Density to Initiate L_{LC} Reflectance

Table 22

Explosive Loading Details for Laser Initiated Units

#	EXPLOSIVE MATERIAL	DOPE	LOADING PRESSURE (K psi) INCREMENT 1	INCREMENT 2	INCREMENT 3
1	HNS	-	50	10	10
2	DIPAM	-	50	10	10
3	RDX	-	50	10	10
4	PETN	-	50	10	10
5	HNS	10% Microballoons 10% Methylene Blue	10	10	10
6	DIPAM	10% Microballoons	10	10	10
7	RDX	10% Methylene Blue	10	10	10
8	PETN	10% Microballoons	10	10	10
9	ALCLC No. 2 (Fe)	-	10	10	10
10	SOS 108	-	10	10	10
11	$BKNO_3$	-	10	10	10
12	Mg-Teflon	-	10	10	10
13	ALCLO No. 2 (Fe)	10% Microballoons	10	10	10
14	SOS108	"	10	10	10
15	$BKNO_3$	"	10	10	10
16	Mg-Teflon	"	10	10	10

NOTE: 1. Doping in first increment (next to window) only.

2. $BKNO_3$ identification = 1P-10

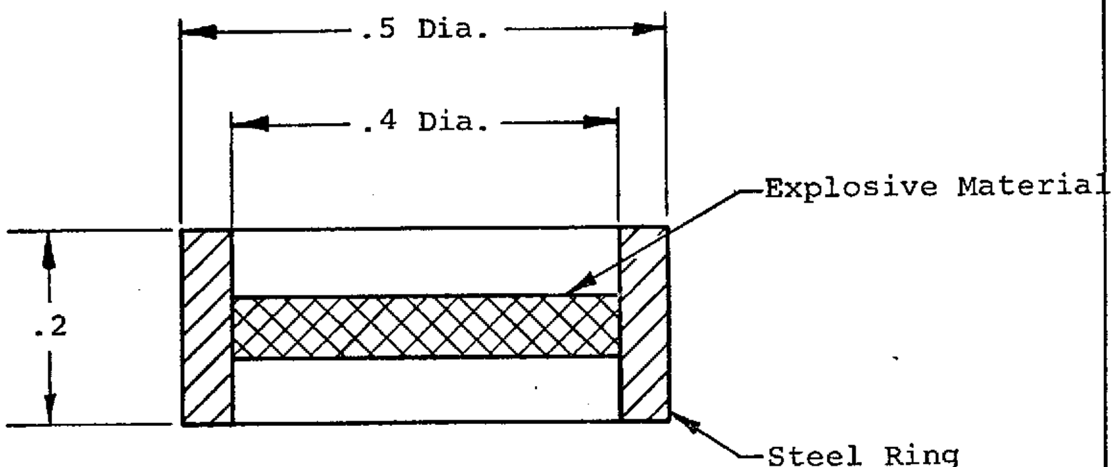


Figure 1

Cross Section of Explosive Material Holder

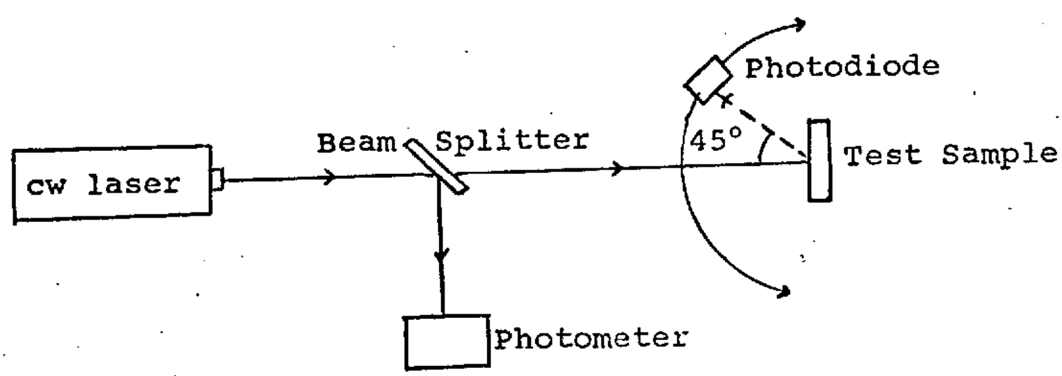
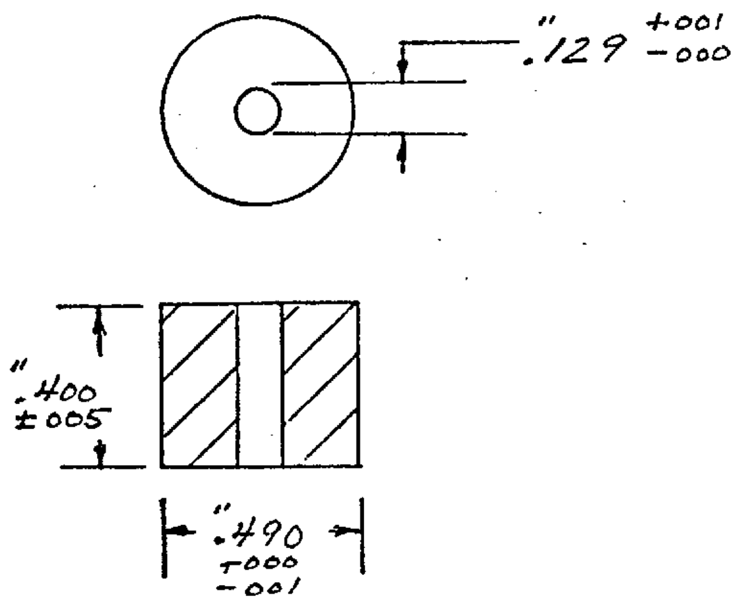


Figure 2

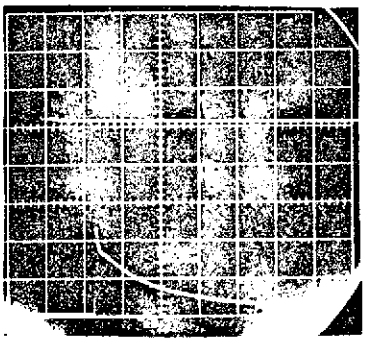
Reflectance Test Schematic for
Absorbtion at 10,600Å

MODIFIED SAMPLE HOLDER
FOR HIGH EXPLOSIVES



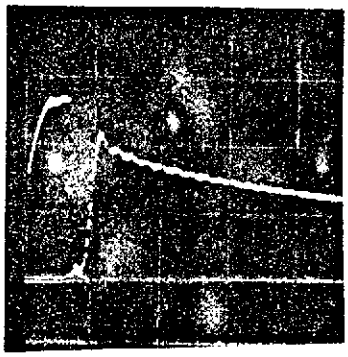
Material: Stainless Steel

Figure 3



Laser Initiated

3.6 joules
200 psi/cm
0.5 millisec/cm



Electrically Initiated

Applied Current - 10.0 amp.
200 psi/cm
2.0 millisec/cm

Figure 4

Pressure/Time Traces for an
Explosive Device Electrically
and Laser Initiated

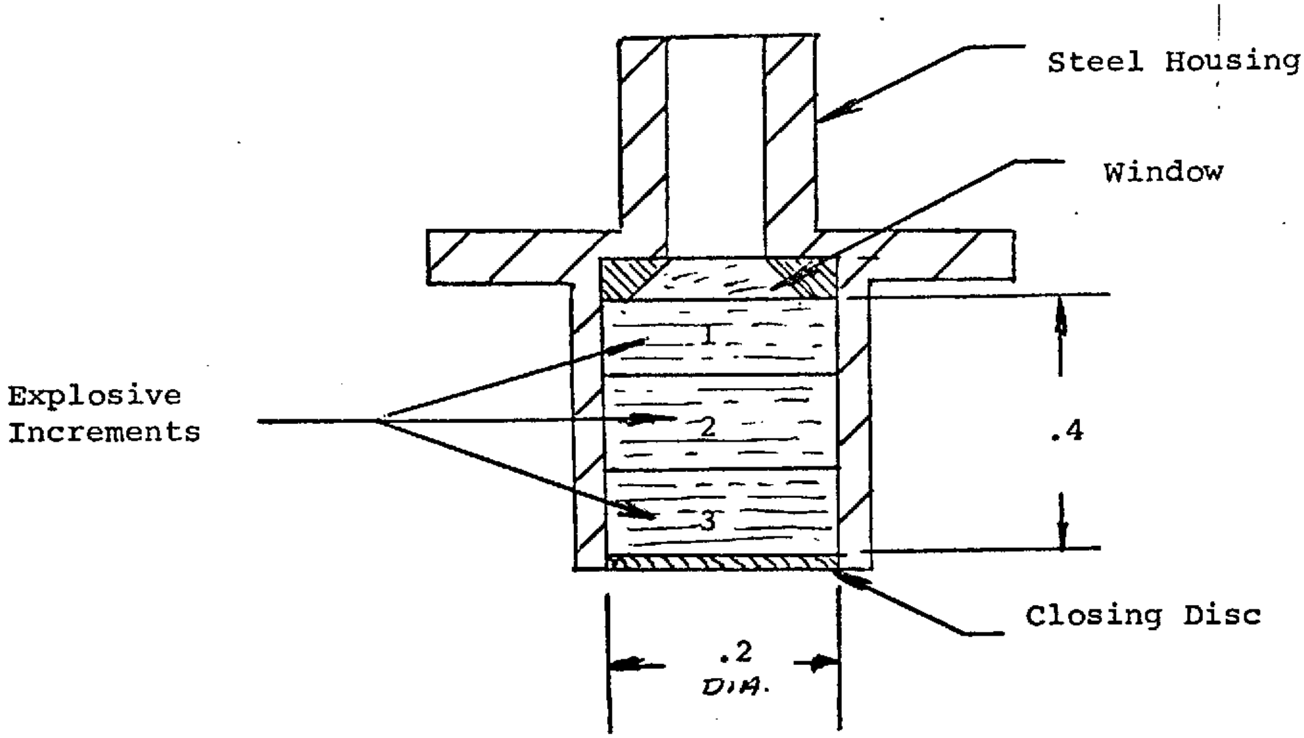


FIGURE 5

TYPICAL LASER INITIATED EXPLOSIVE DEVICE